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THESIS

**STUDY OF MICRO-SIZED TECHNOLOGY, MICRO AIR
VEHICLES, AND DESIGN OF A PAYLOAD CARRYING
FLAPPING WING MICRO AIR VEHICLE**

by

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March 2006

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**STUDY OF MICRO-SIZED TECHNOLOGY, MICRO AIR VEHICLES, AND
DESIGN OF A PAYLOAD CARRYING FLAPPING WING MICRO AIR
VEHICLE**

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ABSTRACT

There has been a recent interest by the military to have platforms capable of operating close to a point of interest without being detected while providing critical surveillance. By providing information that is not readily available, these platforms could provide a useful tool for small unit commanders in potentially life-threatening situations. Highly maneuverable, slow-flying micro air vehicles could fly under canopies, through alleys, or indoors to provide such intelligence. This study consists of a survey of current micro-sized technologies and commercially available components. The findings are presented and used in the design process of a larger, payload-carrying variant of the NPS flapping wing micro air vehicle. The intent is to develop a readily deployable, backpackable, slow-flying micro air vehicle that can be used by smaller-sized ground units in theatre for urban reconnaissance.

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I. INTRODUCTION AND BACKGROUND

A. MOTIVATION

Historically, most airborne missions have been performed by large, expensive, high-performance piloted aircraft. More recently, Unmanned Aerial Vehicles (UAVs) have taken over numerous battlefield observation and reconnaissance missions. The use of UAVs has become very favorable for numerous reasons. First of all, the UAVs are autonomous, or remotely piloted, thus removing the human from the battlefield and the possibility of human casualty. Many UAVs are much smaller than conventional piloted military aircraft. Their reduced size has numerous benefits. Secondly, UAVs are stealthier than their manned counterparts, using the same technology and radar cross section (RCS) reduction methods significantly reducing their chance of being detected by the enemy. In addition, the smaller aircraft also require less logistical support than full size piloted jets. Today's piloted military aircraft are equipped with numerous sensor packages, life support systems, and equipment for pilot interface, which increase weight and cost. Most UAVs can easily be configured for specific missions and carry only the hardware necessary for completing the mission. UAVs can be made lighter and cheaper because they do not need to carry life support systems, ejection seats, video screens, pilot controls, and many other human-interface hardware components. The performance of conventional tactical aircraft is limited by human physiology. UAVs can sustain higher g-forces and g-loading without a pilot onboard. By making the UAV smaller and mission specific, it is a much less expensive liability should a casualty occur. UAV operators require less training than pilots of conventional aircraft. Additionally, as the autonomous capabilities of UAVs are increased, the training requirements of UAV operators will decrease.

Numerous UAVs are currently being used in theatre for observation and reconnaissance because they are less expensive, less detectable, and eliminate the possibility of pilot casualty; however, today's UAVs do have limitations. For example, the RQ-1 Predator necessitates a large amount of ground support. Predator missions must be planned and programmed in advance before the aircraft takes off from a remote

airstrip, which is very time consuming. The process may be sufficient for scheduled surveillance, but offers little help to troops on the ground in impromptu situations. The Sender UAV, developed by Naval Research Laboratory, is a small UAV used in theatre by US soldiers [Ref.1]. The Sender has a four-foot wingspan, weighs ten pounds, and boasts a range of nearly 100 miles. The Sender requires little ground support and can be carried into the theatre by soldiers, making it a very useful platform for certain missions. As the operational demands for UAVs expand, the trend is towards smaller, smarter, and less-expensive vehicles than those being used today. These new missions demand a new class of UAVs called Micro Aerial Vehicles (MAVs). The challenge for today's engineer is to increase the useful payload and autonomous abilities of these vehicles while reducing cost, reducing detectability, reducing the amount of training required for the operator, reducing the platform size, and reducing ground support requirements. In addition, the MAV must be robust enough to be brought into and used on the battlefield.

B. MISSIONS

As with all engineering projects, the first step in the design process is to determine the mission. Once the purpose of the vehicle is known, then specifications or requirements can be determined. Once the desired specifications are known, the design process can continue. Two such sets of mission requirements for MAVs have had a marked influence on the development of MAV technology. First, the Defense Advanced Research Projects Agency (DARPA) defined a set of parameters for a MAV in 2000. Secondly, there are annual national and international MAV competitions that require MAVs to fly specific missions.

The initial missions for MAVs will likely be for the military. In an attempt to determine how the feasibility and practicality of UAVs is affected by size, DARPA has funded numerous Micro Air Vehicle (MAV) projects. DARPA's current specifications for a MAV include a six-inch package size and a weight of less than four ounces. Additional specifications would vary depending on the various reconnaissance missions such a platform would be expected to perform. For example, a hypothetical mission may require the MAV to fly 1km to a point of interest and loiter within 100ft for 30 minutes before returning. Depending on the mission, there is an expressed desire for the aircraft

to be stable in winds up to 25mph, perform tight turns around buildings in urban environments, climb repeatedly to altitudes in the range of 350ft, require minimal pilot training, and have a low cost, possibly less than \$250 to duplicate. For such engineering feats to be accomplished, advances must be made in all aspects of vehicle design including propulsion, power, aerodynamics, materials, and electronics. For this reason, DARPA and other government sources fund numerous projects in many related fields to support MAV development.

The competitors in the annual UAV competitions fly numerous missions. One such mission for MAVS requires flying 600m to a point of interest where a 1.5m symbol is hidden from view by a 3.5m square fence 1.5m high. All support equipment must remain within 100m of the launch site and the team must present a legible image of the symbol to the judges at the launch site. The successful teams are ranked by the aircraft with the smallest linear dimension [Ref.2]. Additional rules are in place for safety and to keep the duplication cost of the vehicles reasonably low.

The design objective of this thesis is to design and build a low speed payload carrying MAV. Low speed MAVs, equipped with cameras, could fly inside buildings or under canopies giving soldiers a new edge in urban warfare and reconnaissance. Although the initial missions for MAVs will be for military observation and reconnaissance, the possibilities are endless. The technology will more than likely expand from the military to other government organizations. For instance, FBI and Police SWAT teams could use MAVs to evaluate terrorist or hostage situations. Fire and rescue units could benefit by sending MAVs into buildings to assess threat or search for survivors before entering themselves. Also, MAVs could be equipped with sensors to sample the environment for chemical, biological, or radiation levels. MAV technology could also be used widely for farmers interrogating the ammonia levels in fields, by the EPA for measuring emissions in industrial smokestacks, monitoring concentrations of chemical spills, or by the forestry and wildlife services to track herds of endangered species. MAV sized models are already commercially available for radio-control hobbyists and as toys.

C. THESIS OBJECTIVE

Many commercial companies are involved in the realm of micro-sized technologies. The military directly researches micro-technology at the Naval Research Lab (NRL) and the Air Force Institute of technology (AFIT). Additionally, many government sources including DARPA fund micro-sized research projects conducted by commercial corporations and educational facilities. The second chapter of this thesis gives an overview of current micro-sized technologies. The important aspects of aircraft design are addressed including aerodynamics, energy storage, power production, propulsive method, structural concerns, avionics, and payload capabilities. Each section is intended to be an unbiased overview of each technology's strengths and weaknesses for MAV operation.

Chapter III of this thesis is designed to highlight how the previous design methods were implemented in the design of MAVs that successfully sustained self-contained flight. No MAV is known to be in mass production or regularly missionized by any organization. The MAVs covered are mostly either one-off prototypes or developmental platforms for payload testing; however, a lesson can be learned from each test flight of every MAV discussed. Each lesson reveals more about the complexities of MAV flight and brings engineers a step closer to the next era of micro air vehicles.

The design of a payload carrying variant of the NPS flapping-wing MAV is outlined in Chapter IV. Sizing theory, construction, modularity, and component selection are discussed. No performance data was available at the time this document was published.

Notable projects in development that show the many promising directions that MAV technology is heading are discussed in Chapter V. The section also highlights many of the current restrictions impeding the testing and development of MAVs.

Finally, this thesis closes by highlighting work that should be continued to further develop the NPS flapping wing MAV into a more capable platform.

II. CURRENT MICRO-SIZED TECHNOLOGY AND MAV DESIGN

A. AERODYNAMICS

The Reynolds number, an indication of the ratio between inertial and viscous effects, of MAV flight is very low. Most aircraft fly at Reynolds numbers in the millions, almost 100 million for the Boeing 747. The flight Reynolds number for various birds and aircraft are plotted against vehicle mass in Figure 1.

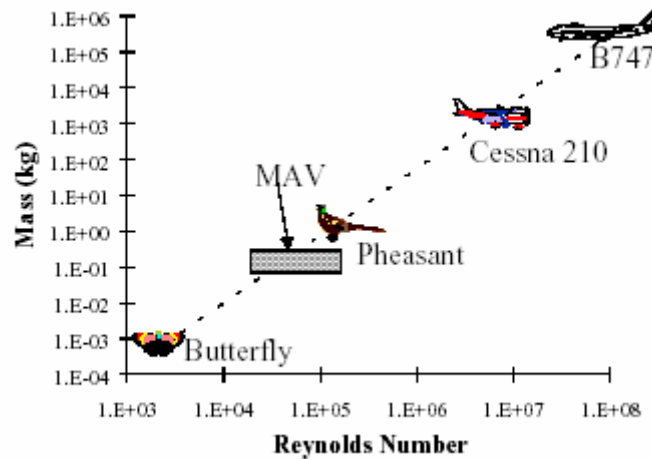


Figure 1. Reynolds number for various flight vehicles [Ref.3]

At Reynolds numbers above about 200,000, many simplifications of the governing equations can often be made to accelerate the design process without significant, or even noticeable, effects. However, these simplifications developed for airfoils at Reynolds number greater than 200,000 are generally inappropriate for designing MAV wings. High Reynolds number flow is dominated by inertial forces and can be adequately simulated using vortex panel method (VPM) codes; however, VPM codes are inadequate at low Reynolds numbers where viscous effects play a larger role. Codes using the Navier-Stokes equations are much more time-consuming and expensive, but are much more accurate than VPM and other inviscid codes at low Reynolds numbers.

Airfoil performance is very sensitive to boundary layer transition and separation. Both separated and transitional flows are sensitive to Reynolds number and pressure

gradient. Typical velocity profiles of a boundary layer are shown in Figure 2. The fluid velocity is zero at the body because of the “no-slip” boundary condition. Away from the surface the velocity is still the freestream velocity. A velocity gradient is setup between the zero velocity and freestream velocities.

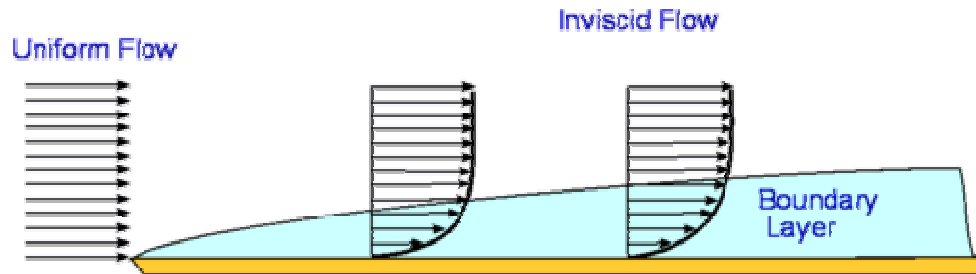


Figure 2. Boundary Layer Velocity Profile [Ref.4]

The layer of fluid between the plate and the point above the plate where the velocity reaches 99% of the freestream velocity is defined as the boundary layer.

Boundary layer flow may be laminar or turbulent. In laminar flow, the flow has distinct layers. The exchange of energy between layers is very limited as opposed to the intense mixing in turbulent flow. Mixing in a turbulent boundary layer allows for a higher exchange of mass, momentum, and energy between layers. Consequently the greater agitation in a turbulent boundary layer produces a steeper velocity gradient near the wall. Typical velocity profiles for laminar and turbulent boundary layers are shown in Figure 3. Laminar boundary layers are typically associated with low Reynolds number flow while turbulent boundary layers are associated with higher Reynolds number flow.

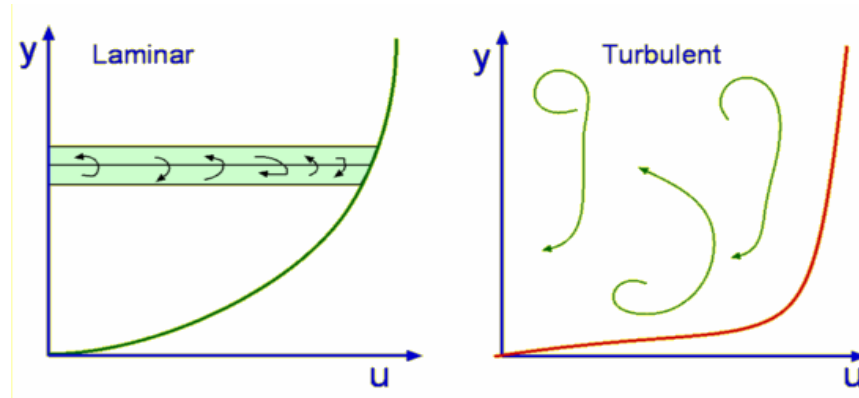


Figure 3. Mixing of boundary layer flow [Ref.4]

Every airfoil has a pressure profile determined by its shape, specifically its thickness, camber and angle of attack. The forward part of the airfoil generally causes a favorable pressure gradient. A sample pressure coefficient is plotted versus chordwise position of an airfoil in Figure 4. Generally the rest of the wing experiences an adverse pressure gradient. A favorable pressure gradient is the area surrounding the wing where pressure is decreasing. In contrast, adverse pressure gradient refers to the section of the wing where pressure is increasing as a function of chordwise position. The magnitude of the gradient is determined by the airfoil's thickness, camber, and angle of attack.

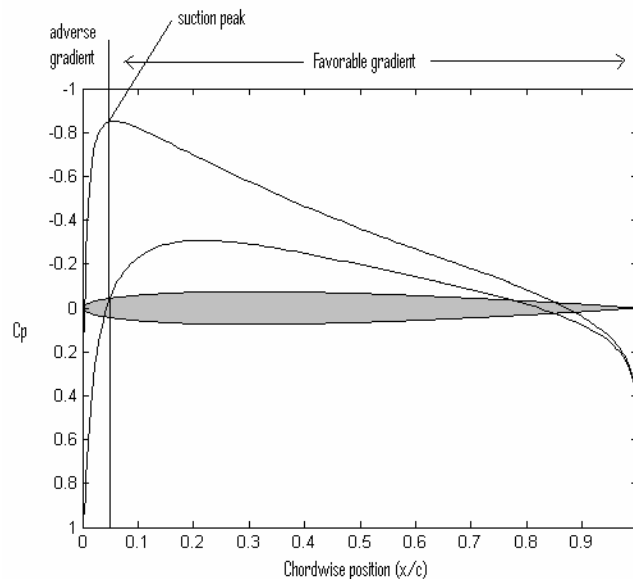


Figure 4. Airfoil pressure distribution

The boundary layer flow experiences shear stress at the wall of the airfoil. The shear stress at the wall removes energy from the flow. This viscous drag slows down the flow in the boundary layer. Favorable pressure gradients oppose this effect thus enabling the flow. Adverse pressure gradients have the opposite effect.

Adverse pressure gradients can have severe effects. The adverse pressure gradient slows down the flow. In particular, the flow close to the airfoil's surface decelerates, where the momentum is already very small. Gradually, the flow retardation reduces the shear stress to zero. Continued retardation of the flow builds flow velocity in the reverse direction. The reversed flow causes a region of recirculating flow that is no longer attached to the body. At this point of zero shear stress the flow is said to be separated.

If the separated flow experiences a favorable pressure gradient or transition to turbulent flow, it may reattach to the airfoil. The area of detached flow between the points of separation and reattachment is called a separation bubble, as shown in Figure 5.

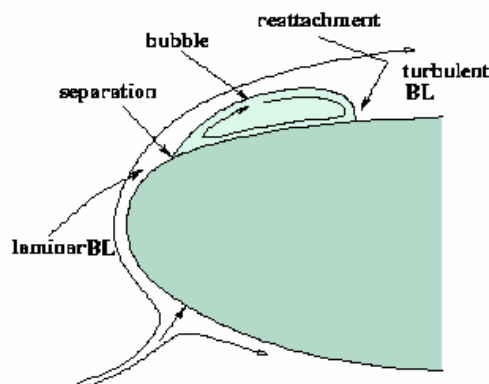


Figure 5. Separation bubble

Some aerodynamicists also extend the definition of a separation bubble to include the case where the flows over the upper and lower surfaces reattach at some point downstream of the airfoil.

Small radio controlled aircraft and larger birds of prey fly at Reynolds numbers between 70,000 and 200,000. In this regime, dependant on the particular airfoil, the separation bubbles may begin to present problems below a certain Reynolds number.

MAVs typically fly at very low Reynolds numbers in the range of 20,000 to 120,000. In addition to their small size and flight speeds, MAVs are generally required to be as compact as possible. This design constraint normally leads to very low aspect ratio wings. Most past experimentation has been done using 2D modeling of infinite span wings. This research is very credible for large aspect ratio wings; however, the aerodynamics of low aspect ratio wings is very different from the aerodynamics of high aspect ratio wings. Volumes of data have been collected for thousands of airfoils for use at high aspect ratio and high Reynolds number flight. Low aspect ratio wings and airfoil shapes have primarily been ignored, especially at low Reynolds numbers, until recent years with the increased interest in MAV flight. Researchers at Notre Dame conducted a program between 1998 and 2000 that consisted of extensive wind tunnel testing of wings with aspect ratios between 0.5 and 2.0 in a Reynolds number range from 50,000 to 150,000. In addition, many researchers have found that simple modifications, especially aspect ratio corrections, used for larger wings do not have the same effect when used on smaller wings in low Reynolds number flow, thus making the aerodynamic design process even more difficult.

Flight under Reynolds number of 50,000 has shown that separation occurs in the laminar region and transition does not occur in time to reattach the flow. For this reason, researchers at Notre Dame declared the regime from 50,000 to 70,000 as the most suitable for early MAV flight and development [Ref.3]. Since the time of their research, experimentation and flight tests have found that boundary layer tripping can be used in this regime to decrease the critical Reynolds number and maintain attached flow. Stable MAV flight under Reynolds number of 50,000 has been demonstrated by using flow entrainment in flapping-wing models and favorable prop-wash effects.

The greatest interest for MAV design is in the range of 20,000 to 70,000. Thousands of small bird species fit into this region of flight. Thin airfoils are normally selected because the hysteresis effects caused by transition of airfoils thicker than about 6% can be very significant. Ideally, an infinitely thin wing should be used. The thickness of the wing drives the size of the adverse pressure gradient. The thinner the wing used, the less severe the magnitude of the adverse pressure gradient. In addition, outside disturbances have a much larger effect on vehicles in low Reynolds number flow.

Although turbulence will make the flight path of a smaller vehicle more unpredictable, simulations show that outside turbulence helps laminar flow to transition earlier (more forward) on the wing's chord.

Some researchers believe MAVs will soon operate at a Reynolds number below 10,000, where flow is completely laminar. The limited modeling and testing of flow at Reynolds numbers this low has been inconclusive; however, there is much speculation into phenomenon such as eddy generation and vortex capturing which allow insects to fly at such low Reynolds numbers.

B. ENERGY STORAGE

1. Combustible Fuels

Many designers consider combustible fuels superior because they have a much higher energy-density than electrical energy storage devices. The energy-density of combustible fuels is roughly three orders of magnitude greater than batteries. Many liquid and gas combustible fuels are readily available [Ref.5]. The weight of fuel powered vehicles also decreases in flight due to fuel depletion which aids performance. However, volatile chemicals must be carried onboard the vehicle. In addition, designers must take into account the potential shifting of the vehicle's center of gravity as fuel is burned.

2. Batteries

Batteries are commercially available with many varying chemistries. Lithium polymer (LiPo) is rapidly becoming the most common chemistry used for electrical systems because it has the highest energy density. Whereas earlier batteries required metal casings, lithium polymer cells save weight by being wrapped in thin metal foil packaging. The correlation between package weight and capacity of current batteries is shown in Figure 6. The batteries' performance specifications are also compared in Table 1.

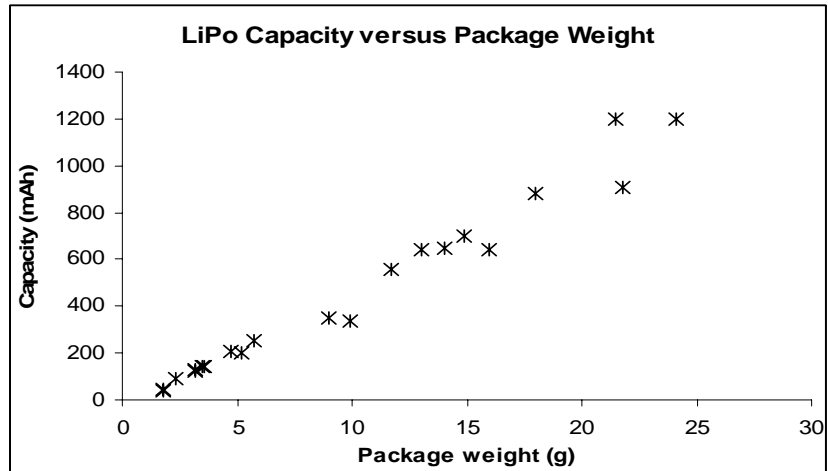


Figure 6. Graphical Comparison of LiPo batteries

Lithium chemistries have many drawbacks including cost, differences in charging and discharging characteristics, and high sensitivity and risk (including explosion) at high operating temperatures.

| Table 1. Lithium Polymer Batteries | | | | |
|------------------------------------|-----------|---------|--------|-----------------|
| Brand | Cap (mAh) | Voltage | Wt (g) | Max Current (A) |
| Kokam | 40 | 3.7 | 1.8 | 0.25 |
| Kokam | 45 | 3.7 | 1.8 | 0.14 |
| E-Tec | 90 | 3.7 | 2.3 | 0.5 |
| Polycell | 120 | 3.7 | 3.2 | 0.24 |
| E-Tec | 130 | 3.7 | 3.2 | 0.6 |
| Kokam | 140 | 3.7 | 3.6 | 1 |
| Kokam | 145 | 3.7 | 3.5 | 0.7 |
| Polycell | 200 | 3.7 | 5.2 | 0.4 |
| E-Tec | 210 | 3.7 | 4.7 | 1.47 |
| E-Tec | 250 | 3.7 | 5.7 | 1.5 |
| Kokam | 340 | 3.7 | 9.9 | 6.8 |
| Kokam | 350 | 3.7 | 9 | 3.5 |
| Kokam | 560 | 3.7 | 11.7 | 1.7 |
| Kokam | 640 | 3.7 | 13 | 4 |
| Kokam | 640 | 3.7 | 16 | 6.2 |
| Polycell | 650 | 3.7 | 14 | 1.3 |
| E-Tec | 700 | 3.7 | 14.9 | 4.2 |
| Kokam | 880 | 3.7 | 18 | 2.6 |
| Polycell | 910 | 3.7 | 21.8 | 1.8 |
| E-Tec | 1200 | 3.7 | 24.1 | 7.2 |
| Kokam | 1200 | 3.7 | 21.5 | 4 |

Non-rechargeable batteries generally offer higher energy density than rechargeable cells of similar chemistry. Many developmental programs sacrifice the higher energy density for the batteries with the ability to be reused.

3. Fuel Cell

Other companies, such as the Ohio based IGR Enterprises Inc., see fuel cells as the future for MAV power sources. IGR is currently developing solid-oxide fuel cells that have several times the energy density of lithium batteries. The fuel cells are very lightweight, but unlike LiPo batteries they are not rechargeable. The fuel cells are therefore one-time use disposable units. IGR expects that a 25g fuel cell roughly the size of a 1cm tall playing card should produce all the power that a MAV would need. The power unit produces energy spontaneously with the addition of the provided non-toxic fuel and ambient air. The unit preheats incoming air and runs to completion, unlike larger refuelable cells. The unit is expected to provide more than one hour and as much as two hours of endurance; although no power estimates are speculated. IGR also argues that the clean and quiet running unit will start reliably, have no cold-weather problems, and has a nearly infinite shelf life requiring no maintenance [Ref.5]. The Hornet MAV has already demonstrated the use of fuel cells as a MAV power supply. Current micro-sized fuel cells, such as that used in the Hornet, are sensitive to moisture. Due to moisture issues, the Hornet's fuel cell only performed three, five-minute flights despite its expected 45 minute endurance.

4. Alternative Energy Generation and Storage

Suggestions have been made towards mechanical-energy storage systems using springs, compressed gas, or flywheels. Other suggestions for electrical power include thermal photovoltaic generators, solar cells, and beamed energy systems. Experiments have been successful in transmitting power using lasers and microwave beams by NASA and NPS, respectively. These tests have been successful for proving the theory; however, they do not produce enough power to support real world MAV operations. In addition, beamed energy methods require line of sight (LOS) to the MAV. The inability to operate out of line of sight is an undesirable weakness in practical MAV missions. AeroVironment has undergone limited research to incorporate solar cells into the Black Widow project for auxiliary power. The feasibility of such systems for use in MAV

propulsion is low because of their low energy and power densities. As a result no significant work is being done to incorporate these technologies into MAV propulsion.

C. POWER PRODUCTION

1. Internal Combustion Engine

Many mainstream UAVs are using internal combustion engines (ICE) for propulsion. Manufacturers have been able to shrink down the ICE powerplants; however, they are still too large for MAVs with a 6in wingspan. Some ICE powered MAVs have been flown, such as those produced by MLB using small Cox two-stroke motors, as shown in Figure 7. These MAVs have been as small as 8.5in in wingspan with no payload. Even if these motors were made smaller, numerous improvements have been recommended by MLB, such as higher compression and a diesel glow conversion to get enough power out of the motors for a significant endurance and payload carrying capacity. For their 6in designs MLB assumed that the smaller-size combustion engines would retain the propulsive efficiency and thrust to weight ratios of the larger models. The Cox Company that provided the off-the-shelf motors for MLB's larger MAVs is not currently undertaking any research or development of any motors smaller than their current selection already on the market [Ref.6].



Figure 7. Cox 0.010, smallest commercially available ICE motor

The losses of internal combustion engines still exist at small sizes and larger design concepts cannot be used. High viscosity oils and fuels will not flow through the small diameter valves because of their high surface tension. Fuels, such as propane, must be used and new methods of lubrication must be investigated. In addition, as combustion motors shrink in size they become difficult to throttle and their reliability diminishes. The small diameter ports on small ICE motors clog easily thus reducing reliability.

2. Electric Motor

The smallest MAVs are using electrical powerplants for propulsion. Electrical powerplants are used on propeller and flapping wing models. Motor technology is advancing, which helps MAV development. Motor manufacturers have been able to shrink down their brushless and coreless motors. Table 2 shows some of the many motors available under 10g.

Although their efficiencies are low, very small coreless motors are commercially available. Companies, such as Didel, are marketing pager motors and gearboxes at varying sizes as small as 0.46g. A table of Didel motors is shown in Chapter IV.

Electrical propulsion systems can be difficult for the novice to design. However, the weight of the battery pack is roughly proportional to the endurance of the aircraft and as battery capacity is increased, the weight of the aircraft increases. Increasing the weight raises the minimum speed of the aircraft and reduces the throttle range. Only so much battery can be added before the aircraft can only generate enough lift at wide open throttle (WOT).

| Table 2. Motors (less than 10g) | | | | | | |
|---------------------------------|---------------|--------|---------------|-------------|-------------|------------|
| Manufacturer | Model | Wt (g) | Rated Voltage | Rated I (A) | Rated P (W) | Rated P/Wt |
| WES-Technik | DC1.3-.02 | 0.8 | 1.3 | 0.015 | 0.02 | 0.025 |
| RoomFlight | Single 4x8mm | 1.14 | 3.5 | 0.19 | 0.67 | 0.588 |
| WES-Technik | DC1.3-.03 | 1.2 | 5.4 | 0.25 | 1.35 | 1.125 |
| WES-Technik | DC1.3-.04 | 1.9 | 3.6 | 0.15 | 0.54 | 0.284 |
| RoomFlight | Dual 4x11mm | 2.03 | 3.5 | 0.17 | 0.6 | 0.296 |
| Falcon | PU03 | 2.2 | 4 | 0.25 | 1 | 0.455 |
| Falcon | PU04 | 2.3 | 3.4 | 0.33 | 1.1 | 0.478 |
| RoomFlight | Single 6x12mm | 3.6 | 3.5 | | | |

For MAVs, electrical motors are more practical than ICE motors. Whereas, small ICE motors are difficult to throttle and unreliable; electric motors are reliable and electronic speed controllers are very small, efficient, and reliable.

3. Artificial Muscle

DARPA had also funded researchers at the Georgia Institute of Technology (GAIT) to produce a reciprocating chemical muscle (RCM). The invention uses a chemical energy source to produce autonomic motion. The RCM was expected to power in-phase flapping wings or legs. In addition, the RCM provides electrical power as a byproduct, which is intended to power the rest of the onboard systems. The project, named Entomopter, has reportedly been progressing slowly after losing DARPA funding [Ref.7]. Currently, the RCM works but it is large in size and produces very little power. Similar projects, such as the electroactive polymer artificial muscle (EPAM) conducted by SRI International, have also been unsuccessful in producing enough power for flapping-wing MAV operation.

D. PROPULSIVE METHOD

1. Propeller

The most common method of propulsion for UAVs is propeller driven. The propeller is quite versatile and can be constructed in many shapes and sizes. A propeller can always be geared and sized to tune flight speed, disc loading, and RPM for the motor selection. The aircraft can be configured as a tractor or pusher with one or multiple propellers.

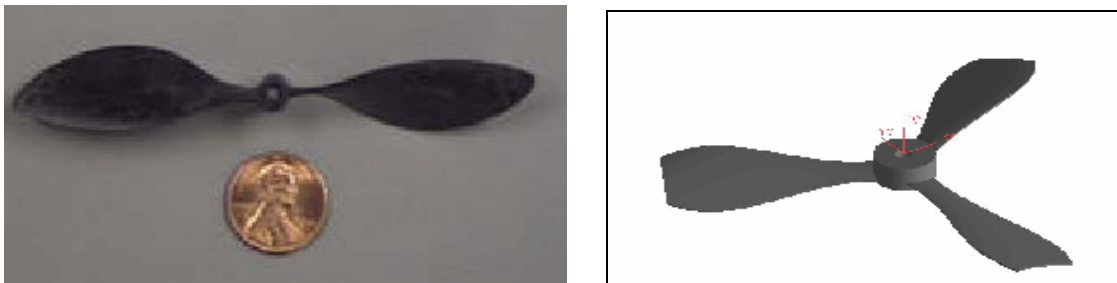


Figure 8. Black Widow (left) and Mesicopter (right) propellers [Ref. 9 and 12]

Testing from multiple sources shows that the efficiency of traditionally designed propellers with small diameters is low. Based on the feasibility study done by the RAND Corporation, MLB uses a 50% propeller efficiency in their optimization code [Ref.6]. Although traditional propeller designs are not efficient at small diameters, AeroVironment has designed and fabricated unconventional small-diameter propellers for their MAVs with much higher efficiencies, up to 80% [Ref.8]. Stanford researchers have designed and tested smaller propellers with diameters as low as 1.5cm [Ref.9]. AeroVironment and Stanford's propeller designs are shown in Figure 8. Most propeller-driven MAVs fly at high speeds because propeller efficiencies are best at high Reynolds number. High chord Reynolds number is generally achieved using high RPMs.

2. Flapping Wing

Numerous projects have been based around the flapping-wing flight of bugs and birds. Some researchers believe that these projects will be the most efficient form of flight at very low Reynolds numbers. Many believe that the ability to copy the flapping flight of one of nature's creations such as a hummingbird, would give MAVs greater endurance and maneuverability. Hummingbirds are able to swoop down from nests at high speed, hover for extended periods of time, and even exhibit great endurance migrating miles over water without eating. These high levels of performance are desired for MAVs and researchers believe that all of these attributes in nature can be achieved by MAVs.

Birds' bodies are very sophisticated and designed for flight. For instance, feather shafts are durable and hollow for high strength and low density. The aspect ratio of a bird's wings can quickly be adjusted in a wide range, aiding in both high speed and high endurance flight. Birds actively use their tail as a rear stabilizer. They can change the aspect ratio, twist it, and elevate it at the same time. During all of these complicated airborne adjustments and corrections, the bird's head provides a stable platform for its eyes. All of these attributes that make a bird's flight so versatile are very difficult to incorporate into mechanical systems. In addition, if these attributes could be copied mechanically, all or in part, they would require a very sophisticated control system to make the complicated in-flight adjustments that birds make involuntarily.

Models have been constructed that flap their wings almost identically to a bird's wings. Although many of the larger models have not flown, many smaller projects such as AeroVironment's Microbat have been successful. The same trend is inherent in nature: although the smallest birds and bugs are able to take off from a standstill, birds with high wing loadings, such as the albatross, have a very difficult time taking off. Flapping-wing flight requires constant acceleration of the wing's mass, explaining the dependence of agility on wingloading.

The phenomenon by which a flapping wing produces thrust has attracted much attention since the early 1900s. Knoller and Betz theorized that the resultant force on a flapping wing had lift and thrust components, as shown in Figure 9. Katzmayr conducted wind tunnel tests to verify that the sinusoidally oscillating effective angle of attack of the airfoil in the freestream produced a thrust force [Ref.10].

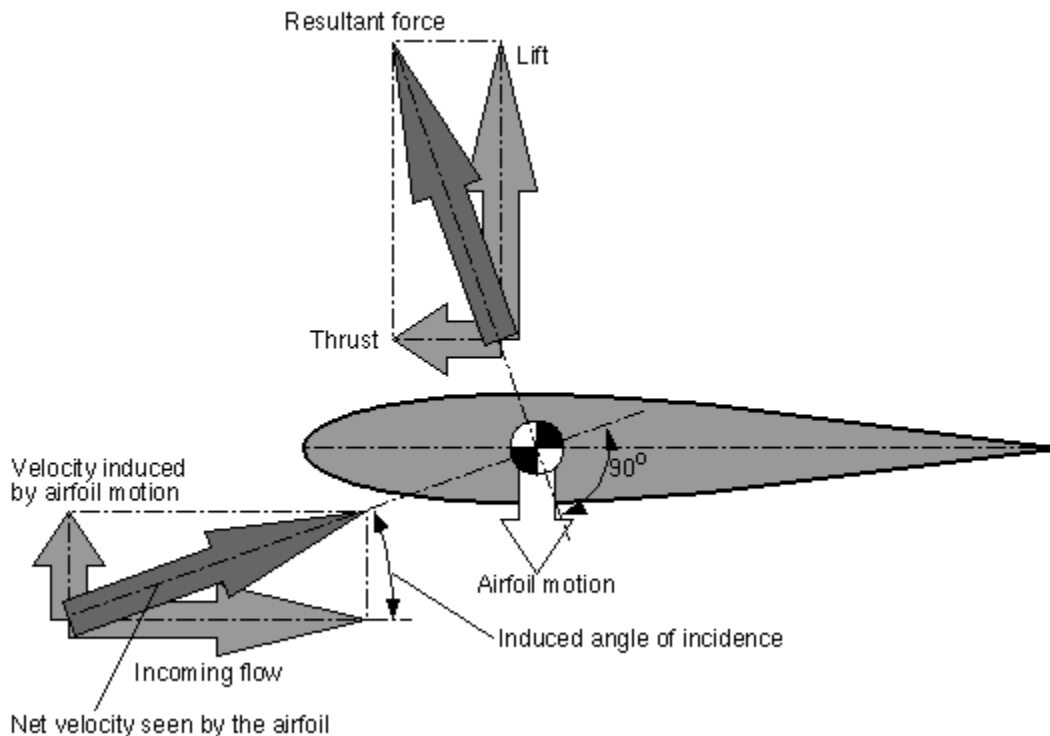


Figure 9. Resultant force on a plunging airfoil [Ref.19]

Since these initial theories and discoveries, many experiments have been conducted with flapping wings in numerous configurations. Aircraft using a single trailing flapping wing

are mechanically unbalanced. Mechanically unbalanced systems are inefficient because the net torque exerted on the main structure causes the aircraft to wriggle. Energy intended to flap the wings is lost flapping the main structure. Schmidt's wave propeller was a configuration implementing a flapping wing in tandem with a fixed trailing wing, as seen in Figure 10. In linear theory the wave propeller had a higher efficiency, although in viscous flow the small gain was overcome by the increased viscous drag. The wave propeller was also mechanically unbalanced.



Figure 10. Schmidt's wave propeller configuration [Ref.10]

The opposed plunge/plunge configuration, developed by Jones and Platzer and shown in Figure 11, is a symmetrical configuration that is mechanically and aerodynamically balanced.

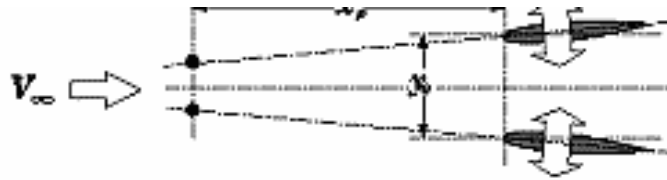


Figure 11. Jones and Platzer's opposed pitch/plunge configuration [Ref.10]

Keiser was one of the pioneers of clap-fling designs. His model has four wings hinged at the main structure. A model of Keiser's flapping wing model is shown in Figure 12.

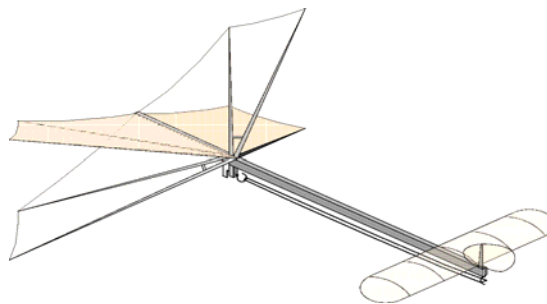


Figure 12. Keiser's 4-wing clap-fling configuration [Ref.19]

The pair of wings on each side clap together then fling apart. Many organizations are interested in the development of MAVs that mimic bird flight. Such configurations have two wings (left and right) that are hinged at the main structure. One such configuration is AeroVironment's Microbat, shown in Figure 13.

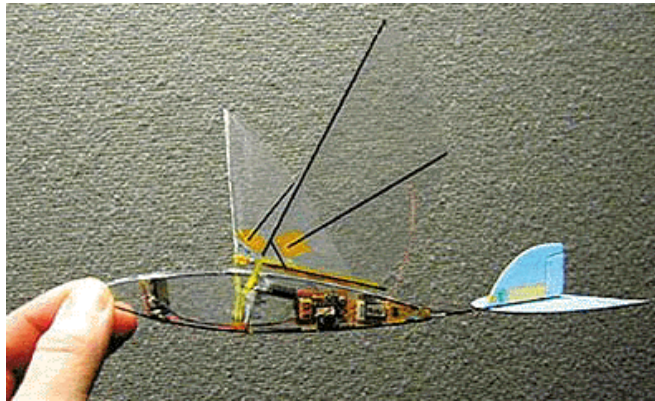


Figure 13. Microbat biomimetic configuration [Ref.10]

E. CONSTRUCTION METHODS

Current MAVs take advantage of recent developments in composite technology. Composites have many benefits for MAV construction. A composite combines two or more materials for a new material with better mechanical properties. A common example is the combination of glass fibers and epoxy. By itself, epoxy hardens into a very brittle plastic. Glass fibers have very good tensile strength but are also brittle and do not hold their shape. When combined, the fiberglass epoxy composite exhibits high strength and low weight. Bending stiffness goes with the cube of thickness; therefore, many times layers of a composite are separated by a layer of honeycomb, foam, or balsa to increase the dimension of the composite piece while keeping weight low. These pieces are called sandwich composites. Composites are normally laid over a mold (male-mold), inside a mold (female-mold), or between a male and female mold. Fibers are normally glass, carbon, or aramid and come as chopped media, as individual fibers, or as woven sheets. Sheets come in various weights, thicknesses, and strand orientations. Various epoxies and glues also have different properties. Epoxy viscosity affects how well the fiber will wet-out. Epoxies also differ in their hardening requirements. Some epoxies or glues may

harden quickly at room temperature; some must be baked in an oven or autoclave. The thermal cycle can have a huge effect on the properties of the composite.

Many airframes such as the Black Widow are foam-centered sandwich composites. The shape is established by hotwiring or CNC milling a piece of foam. The foam male mold is sacrificed and becomes the center section of the sandwich composite after being covered by fiberglass or carbon. Hotwiring is performed by passing a large current through a thin gauge wire. The high resistance of the thin wire causes it to get “hot” and melt through the foam. Linoleum templates are normally used to control the cutting path of the wire. Advanced methods include CNC milling the foam or using computers to control the path of the hotwire.

Some MAVs, such as University of Florida’s Morphing Micro Air and Land Vehicle (MMALV), have hollow shells. These shells are made in a similar process, except the mold is covered in release media and separated from the part after the epoxy has hardened.

MAVs are very easy to overbuild because they experience very small forces while in flight, especially at low speeds. Weight is kept low by careful construction practices. Removing excess epoxy from a wet composite with a squeegee or by vacuum bagging, limiting amounts of glue to bond parts, and trimming lightly loaded areas of larger parts are methods used to lighten vehicles without sacrificing much strength.

Although sandwich composites offer great strength to weight, the structural properties of the MAV must support the mission requirements. For example, wings may be desired to roll-up or compact to fit the MAV into a small container for transport or launch. Some experiments are also being done with MAVs, whose wings fold up and retract as the leading edge is swept back, minimizing the MAV’s wingspan allowing it to crawl through smaller openings. Materials and composites used as structures and coverings must be intelligently chosen based on the MAV mission requirements. Some MAVs continue to use conventional covering materials, such as those listed in Table-3, for wing surfaces.

| Table 3. Covering Material | | | |
|----------------------------|----------------------------|------------------------|-----------------|
| Supplier | Type | Wt (g/m ²) | thickness (mil) |
| IMS | Polimicro-Film | 1.3 | 0.035 |
| WES-Technik | 0.002mm mylar(x12in) | 2.2 | 0.08 |
| IMS | 0.012oz condenser paper | 3.7 | |
| Office Depot | waste can liner | 5.8 | |
| IMS | 0.020oz condenser paper | 6.1 | |
| WES-Technik | 0.004mm alum mylar (x24in) | 6.8 | 0.16 |
| WES-Technik | 0.005mm mylar (x24in) | 7 | 0.2 |

F. ONBOARD ELECTRONICS

Few universities or companies, such as AeroVironment, are capable of producing their own onboard electronics. The Black Widow has its own fully proportional receiver and limited autopilot. The autopilot includes one-axis magnetometers, single-channel piezoelectric gyro, and pitot-static pressure sensors [Ref.11]. Whereas AeroVironment has engineered its own custom lightweight system for the Black Widow, most engineering projects are cost-limited to current off-the-shelf electronics. Each MAV needs a radio receiver. The receiver transfers multiple channels of commands from the user to the servomechanisms on the aircraft. The motor will run at wide open throttle unless a speed controller is used. An electronic speed controller (ESC) controls the voltage or the duty cycle of the current going to the motor to control its speed. Some receivers have an ESC built in. Examples of receivers for servos are given in Table 4. Control surfaces and other moving parts are controlled by servos or magnetic actuators. Servos must be controlled by displacement-proportional receivers whereas magnetic actuators are force-proportional devices. Unlike magnetic actuators, servos receive their signal separately from their power. Commercially available actuators are much lighter than conventional servos although they can have high power demands for their size. Approximately 0.5W is needed for a hard-over deflection. Commercially available autopilots and GPS receivers are getting smaller but are still too large and heavy for MAV use.

| Table 4. Receivers for Servos (less than 15g) | | | | | | |
|---|------------|----------|------|----------|--------|--------------|
| Manufacturer | Model | MHz | Mode | channels | Wt (g) | Built-in ESC |
| Leichty | Micro | 27 | AM | 1 | 0.15 | No |
| Leichty | Mini | 27 | AM | 1 | 0.18 | No |
| Leichty | Mini | 27 | AM | 3 | 0.4 | No |
| Leichty | Mini | 27 | AM | 3 | 0.5 | Yes |
| JMP | ServoCombo | 72 | FM | 4 | 2.4 | Yes |
| Gasparin | PENTA | 35/40/72 | FM | 5 | 2.4 | No |
| Sky Hooks & Rigging | RX72 | 72 | FM | 5 | 2.7 | No |

Projects with higher budgets can afford to fabricate, repackage, or have circuits fabricated and save weight over COTS components. Repackaging is a weight-reduction method that involves partially disassembling a circuit, removing unnecessary components, and possibly replacing other components before reassembling the entire circuit. Companies such as Maxtek Components will custom fabricate multichip modules (MCMs). MCMs are entire circuits assembled on either an organic, flex, or ceramic substrate. Using sophisticated laser trimming and IC die fabrication techniques, MCMs can provide high speed, high signal integrity, and high density data transfer. MCMs offer many benefits for MAV avionics including digital processing and wireless data transfer.

G. CURRENT PAYLOADS

Currently, the only payload being carried by MAVs are cameras and video transmitters. Most cameras being used are recent developments since MIT successfully built the first microchip camera. The current off-of-the shelf cameras vary in resolution and power requirements. Most are sold as indoor “spy” cameras through commercial “spy” companies. Units normally have wide aperture lenses encased by heavy metal protective cases and have large wiring connections. Few are designed directly with MAV applications in mind; however, weight can be significantly reduced by removing the protective casings and by modifying the included wiring. Most units also have built-in voltage regulators. Bypassing such circuits is sometimes useful when integrating such equipment into the MAV power distribution system. Most lenses can be focused; however, most programs adjust focus on the ground and do not equip the MAV with the extra servo required for in-flight focusing or zoom.

The camera is generally paired with a video transmitter. Similarly, very lightweight transmitters have been in production only as of late. Transmitters have varying power requirements and operational frequencies. Lower power transmitters are used when lightweight requirements limit onboard payload power. Low power transmitters have less range and require high gain receivers on the ground. High gain receivers require directional antennas on the ground to be accurately aligned with the signal transmitted by the MAV.

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III. SUCCESSFUL MAV PROTOTYPES

A. AEROVIRONMENT BLACK WIDOW

In 1999, AeroVironment won DARPA's Award for Outstanding Performance by a Small Business Innovation Research Contractor and the Shepherds Press Unmanned Vehicles Magazine Readership Design Award for the Black Widow MAV. The Black Widow is a conventional propeller driven MAV. It flies using a hotwired foam rectangular wing with tapered corners, as shown in Figure 14. The propeller is directly driven. The electrical propulsion system is powered by Lithium batteries. The MAV has a 6in wingspan and configuration-dependant weight of around 80g.



Figure 14. AeroVironment Black Widow [Ref.12]

The Black Widow has demonstrated an endurance of 30-minutes, maximum range of 1.8km, and maximum altitude of 769 feet. The MAV flies at 30 mph. The custom designed and built electronics, include a 3g color camera, 2g video transmitter, 5g fully proportional radio control receiver, 0.5g actuators, and an autopilot. The autopilot includes single-axis magnetometer, piezoelectric gyro, and pitot-static pressure sensors. With these components and a central processor, the autopilot is currently capable of maintaining airspeed, altitude, or heading. The autopilot also features active yaw damping. Similar to all MAVs, in flight, the Black Widow is extremely difficult to

observe and must be flown via downlinked video imagery and sensor data when operated more than a short distance from the pilot [Ref.12].

B. AEROVIRONMENT WASP

In August of 2002 the Wasp recorded the longest flight of a MAV at 107 minutes. The Wasp, shown in Figure 15, was developed as part of DARPA's Synthetic Multifunction Materials Program by Telcordia Technologies and NRL and built by AeroVironment. The project's intent was to improve overall efficiency and performance by combining the function of structure with other critical aircraft functions. The Wasp combined the function of power-supply and wing-structure. The multifunctional structure/battery supplies electrical energy for the motor and avionics and doubles as a mechanical structure for transferring aerodynamic forces on the main wing. In essence, the 4.25 ounce Wasp plastic lithium-ion battery (6 ounce vehicle weight) was designed, shaped, and fabricated to be the main lifting wing. The 13 inch wingspan flying wing configuration is equipped with off-the-shelf avionics including a 3-channel receiver controlling throttle, rudder, and elevator. The Wasp did not carry a camera, autopilot, or flight augmentation system [Ref.13].



Figure 15. AeroVironment Wasp [Ref.13]

C. AEROVIRONMENT HORNET

In conjunction with Lynntech Incorporated, AeroVironment completed the first documented flight of a MAV powered entirely by a hydrogen fuel cell as part of DARPA's Synthetic Multifunction Materials Program in March of 2003. The hydrogen generator and fuel cell was developed and tested by Lynntech. The fuel cell was fabricated using a stiff metal mesh that doubles as the wing's mechanical structure. No batteries were carried onboard; the motor and all avionics were powered by the fuel cell. The 6 ounce MAV was a flying-wing configuration with a 15 inch wingspan. A three-channel receiver controlled the rudder, elevator, and rate of hydrogen generation. The Hornet, shown in Figure 16, was developed to show the potential of fuel cells for powering high endurance MAVs. Although the fuel cell's endurance was designed to be 45 minutes, the Hornet accomplished three flights for a total endurance of 15 minutes, due to moisture problems in the fuel cell. The Hornet did not carry a camera, autopilot, or flight augmentation system [Ref.13].

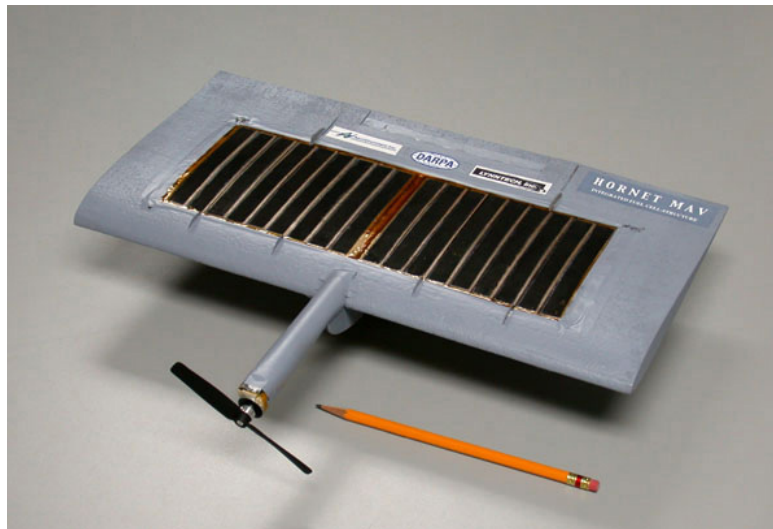


Figure 16. AeroVironment Hornet [Ref.13]

D. AEROVIRONMENT MICROBAT

The Microbat, shown in Figure 17, is a flapping MAV designed in conjunction by CalTech, UCLA, and AeroVironment for DARPA. The motor flaps the left and right wings in a near sinusoidal motion with a minimal phase difference. The Microbat was tested using flap amplitudes from 40 to 60 degrees (comparable to flap amplitudes used

by small birds.) Although intended to be tailless, the complex flight control system necessary to differentially control both Microbat wings for three-axis control was abandoned for a simpler tailed design. Turning, speed, and climb rate were controlled by rudder, elevators, and throttle respectively. The Black Widow inspired 3-channel receiver comprised only 0.9g of the vehicle's 14g total mass. The Microbat used electrically stimulated muscle wires for deflecting its control surfaces. Originally, a 50mAh NiCd single cell battery weighing 3.5g powered the coreless DC brush (vibrating pager and mobile-phone) motor. In flight tests, the NiCd cell powered the Microbat for a 42 second flight in 2000. After numerous modifications, including the replacement of the NiCd cell for two small rechargeable lithium batteries, AeroVironment has achieved 25 minutes in flight [Ref.8].

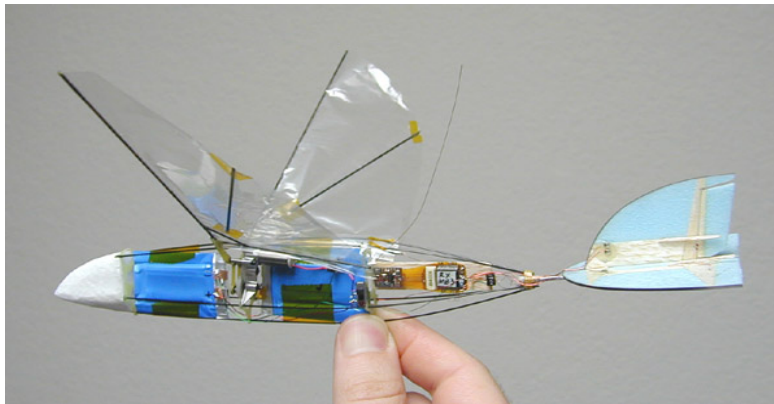


Figure 17. AeroVironment Microbat [Ref.8]

E. IAI MOSQUITO

The Mosquito, shown in Figure 18, flew its first flight in January of 2003. The 40 minute flight was flown by the original 250g, 12 inch wingspan design. Little performance or avionics data has been released by IAI. IAI has published the Mosquito's ability to stream live video from and onboard camera. IAI is currently developing the Mosquito 1.5 in hopes to achieve 60 minutes of flight endurance. The Mosquito 1.5's advances include two gimbals and electronic image stabilization software for enhanced video quality. IAI is also developing custom avionics for fully autonomous mission capability [Ref.14].

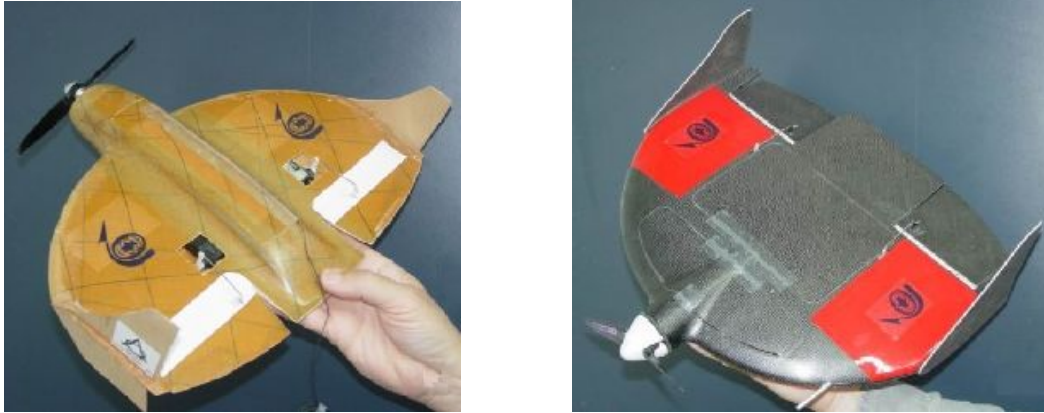


Figure 18. Mosquito 1.0 (left) and Mosquito 1.5 (right) [Ref.14]

F. LOCKHEED MARTIN MICROSTAR

Lockheed's initial teardrop bodied cropped delta wing design had a single vertical stabilizer, as shown in Figure 19. The final platform swapped the vertical stabilizer for winglets and added a propeller in a tractor configuration vice the original pusher configuration. Test platforms were constructed with 6.0, 9.0, 15.0, and 24.0 inch wingspans. Maxtek Components fabricated the 5.0g navigation system including processor and data MCMs. The autopilot accepted directional commands from the ground station and was capable of maintaining heading or orbiting a target. MicroSTAR flight testing demonstrated altitudes up to 200ft, 30mph max velocity, and an endurance of 20 minutes. The MicroSTAR project never entered mass-production; however, Lockheed continues to develop the autopilot system for use on its larger UAVs [Ref.15 and 16].



Figure 19. Lockheed Martin MicroSTAR [Ref.24]

G. MLB FIXED WING ELECTRIC

This aircraft completed a one minute flight using a 0.18 watt-hour nickel-cadmium battery pack and two electric motors in a tractor configuration. The 9in wingspan model's configuration was achieved through trial and error. Twin engines kept disc loading low because the motors operated at high RPM for propeller efficiency. The airframe used a one-channel commercially available receiver for rudder deflection. Flight testing resulted in a maximum altitude of 40 feet and a cruise velocity of 27 fps. The limited performance capabilities of the aircraft made it unstable in moderate winds or turbulence. This design, along with the Flyswatter and Helirocket, were the first of many MAV designs tested by MLB starting in 1997 [Ref.17].

H. MLB FLYSWATTER

This 8.5 inch wingspan model was powered by a Cox 0.010 cubic inch internal combustion engine. The aircraft configuration included a cambered rectangular wing and winglets, as shown in Figure 20.

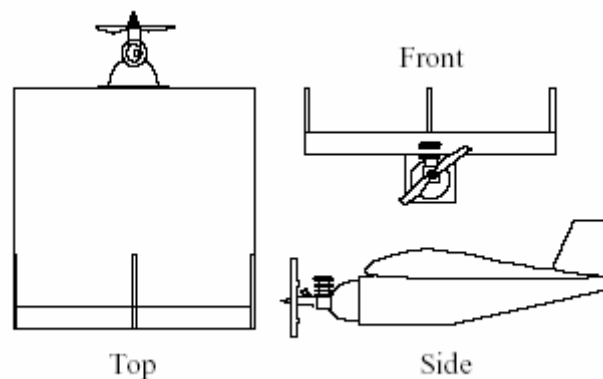


Figure 20. MLB Flyswatter [Ref.17]

The Flyswatter was controlled by a two channel commercially available receiver. Flight testing at full throttle resulted in a two-minute endurance, 20 foot turning radius, altitudes greater than 50 feet, and 30fps velocity. The aircraft's configuration was based around a low aspect ratio lifting wing. The development of the tip vortex played a large role in sustaining lift at high angles of attack. The increased lift improved the aircraft's

performance in turns and at low speeds. In addition, the Flyswatter flight tests showed that lower aspect ratios and higher wing loadings decreased gust sensitivity. Flyswatter was stable in winds up to 15mph whereas their previous fixed-wing model could not sustain flight in winds over 5mph. As with most MAVs, rudder control provided sufficient roll authority [Ref.17].

I. MLB HELIROCKET

Powered by the Cox 0.049 cubic inch internal combustion engine, the MLB Helirocket turned a 7 inch propeller and controlled flight using four control vanes, as shown in Figure 21. Using a 0.4 ounce fuel tank, the Helirocket sustained stable flight for 2.5 minutes. The VTOL aircraft has been flown with payloads up to 1.5 ounces. The Helirocket has demonstrated stability in translational flight in light winds [Ref.17].

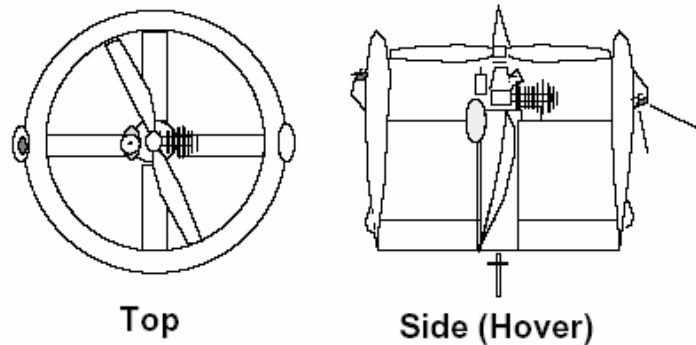


Figure 21. MLB Helirocket [Ref.6]

J. MLB TROCHOID

MLB Company's most recent and successful MAV, the Trochoid, had a wingspan of less than 8 inches. The configuration was a near delta wing with fixed twin vertical stabilizers. Unlike most MAVs, the Trochoid used ailerons for roll control as opposed to relying on the strong yaw-roll coupling of rudders. Flight tests have demonstrated flight speeds from 10 to 60mph and a 15ft turn radius. Trochoid was able to sustain stable flight in winds up to 20mph.

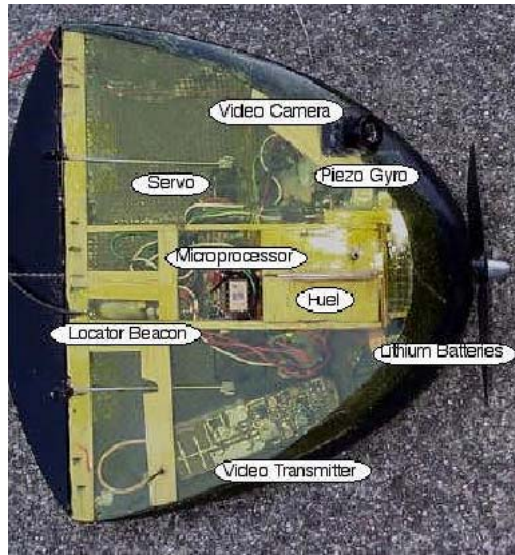


Figure 22. MLB Trochoid [Ref.18]

The Trochoid MAV, shown in Figure 22, was equipped with a camera and video transmitter. The gas powered MAV used a small lithium battery for payload and auxiliary power. An active stability augmentation system included a microprocessor and gyros and was capable of yaw damping. No other capabilities of the augmentation system have been specified. A locator beacon was also integrated among the MAVs internal components [Ref.6].

K. NPS FLAPPING-WING MAV

The NPS flapping-wing MAV, shown in Figure 23, has a large lifting wing forward and two counter-plunging flapping wings trailing behind the main wing. This design is superior to many configurations because the flapping wings are mechanically balanced. It is also believed that the symmetry of the twin wings may mimic ground effect. Testing of the flapping wing model in a smoke-tunnel shows that the phenomenon of flow entrainment keeps the flow close to the main wings. This effect makes the aircraft very resistant to the unstable and unpredictable effects of separated flow. 10.5g and 13.4g models have been successfully flown. A 2-channel receiver controls rudder deflection and throttle setting. Both altitude and velocity are controlled using throttle position. The MAV must be trimmed for level-flight velocity before launch. Roll-yaw coupling and rudder are used for turning. The MAV is best suited for low speeds slightly

above walking speed, roughly between 4 and 10 mph. The MAV has demonstrated rapid stall recovery. Under power the model generally recovers from stall in less than one chord length. Test flights have been flown for 12 minutes with battery to spare. The MAV should be able to fly for 15-20 minutes. The standard NPS flapping wing MAV does not carry a payload [Ref.18 and 19].

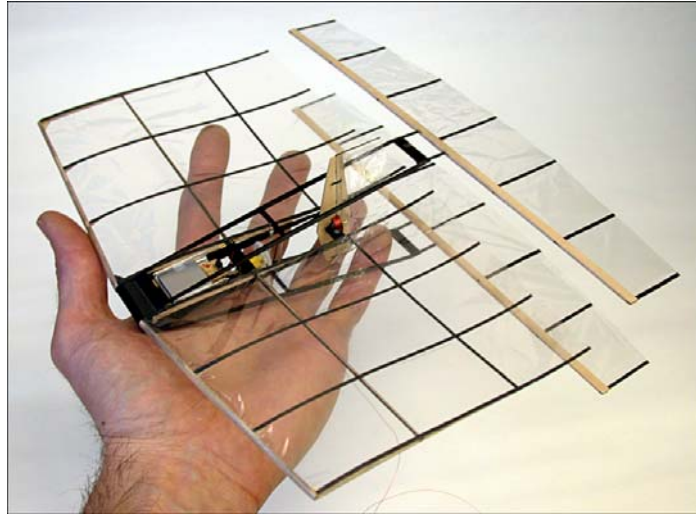


Figure 23. NPS Flapping Wing MAV [Ref.19]

L. NRL MITE

The MITE is a dual propeller fixed wing MAV. The design has a fixed chord of nine inches. MITE variants have been flown with wingspans of 8.0, 14.5, 12.0, and 18.5 inches. The 14.5 inch wingspan MITE2 can carry a one ounce payload. In flight tests the MITE2 has demonstrated 20 minute endurance at speeds from 10 to 20mph. The MITE2 carries an analog camera and is remotely piloted only, although autopilot systems are being developed. The MITE3 wingspan was reduced to 12.0 inches after swapping to lithium batteries and more advanced avionics. The latest variant, MITE4 shown in Figure 24, is a 18.5 inch wingspan configuration with more powerful coreless motors for testing developmental payloads up to 4.0 ounces. Performance numbers are not readily available because each variant has multiple configurations using different battery packs, motor gearing ratios, and propellers. Many MAVs experience unpredictable rolling, especially at low velocities such as during launch due to torque in the body from the motor. The MITE's counter-rotating propeller design avoids the torque problem that

many MAVs can experience. The propeller wash also has a net upward component at the leading edge of the wing because of the rotation directions of the propellers. The upward velocity causes an increase in effective angle of attack. The increased effective angle of attack can be used to gain aerodynamic benefits [Ref.20].



Figure 24. NRL MITE4 [Ref.20]

IV. DESIGN OF A PAYLOAD CARRYING VARIANT OF THE NPS FLAPPING WING MAV

A. SELECTION OF NPS FLAPPING WING CONFIGURATION

With all of today's technological advances in reconnaissance, today's platoon commander does not have any more idea of what waits over the hill than a battalion commander had in any other past war. Larger UAVs provide good intelligence for mission planners in the grander scheme of the war; however, it is not best suited for helping smaller units in theatre. A new platform is needed to give the smaller ground unit a better perspective. For example, before marines in Afghanistan raid a possibly hostile city from door to door, a small MAV could transmit video while flying between buildings and through alleys. This video would reveal hostile soldiers and possible ambushes. In addition the intelligence is a powerful tool for the unit commander in planning how to enter the city.

For this project a MAV was desired that was capable of transmitting live video while flying in the urban environment. Possible missions include, but are not limited to, flying under canopies and inside buildings. Conventional propeller driven MAVs can carry heavy payloads and are efficient at high speeds. For the low flight speeds desired a flapping wing configuration was chosen. The NPS flapping-wing aircraft was chosen as the configuration for this project because it operates at low speeds, is very stable, and is relatively easy for a pilot to control.

B. AIRFRAME SIZING THEORY AND CONSTRUCTION

1. Sizing Theory

The dynamics of MAV flight is a discipline that has not been explored in depth. No simple equations exist for use in the designing and sizing of MAVs in low Reynolds number flight. For this MAV, it was assumed that gross takeoff weight is linearly related to planform area of the main wing. This relation is surely not valid for large dimensional changes of the vehicle; however, for the small change in size being made, this assumption is reasonable. A number of potential components were selected for the final vehicle, thus

allowing a baseline weight distribution to be generated. The weight estimation showed that an airframe proportionately increased to a wingspan of 15.0 inches should provide adequate lift if the previous assumptions were valid.

2. Lifting Wing

The main lifting wing was built maintaining the same aspect ratio as the previous NPS flapping wing MAV. The main wing is a thin sheet of plastic film affixed to a composite frame. The composite frame has a carbon/balsa sandwich composite leading edge and main spar. Additional carbon fiber composite ribs stiffen the main wing. A carbon/balsa sandwich composite rib spans from the leading edge to the main spar at the root of each wing. The wings are not permanently fixed to the main structure, allowing the dihedral, camber, and twist to be adjusted simply with shims between the root rib and main structure. This also allows for wings to be swapped out for various payload sizes.

3. Main Structure

The main structure of the MAV is constructed of carbon/balsa sandwich composite pieces that are cemented together. The main structure was proportionately increased in size from previous NPS flapping wing MAVs. The size of the structure is dependant on the aircraft's flap amplitude. The structure must be made wide enough to fit the crank. The motor and gearbox is mounted in the rear of the main structure (in the middle of the MAV) and the front section was left void. The front payload compartment is designed to allow swapping of internal components such as batteries, receivers, and cameras.

4. Flapping Wing

The flapping wings are thin sheets of plastic film affixed to a balsa spar and carbon fiber composite ribs. Carbon fiber strips are used as an elastic joint to connect the carbon/balsa composite swingarms to the flapping wings and main structure. The dimensions of the flapping wings are proportional to previous NPS flapping wing MAVs.

5. Control Surfaces

For this MAV control surfaces were not permanently attached. A mounting plate is present in the rear of the main structure for swapping out different stabilizers of various sizes. This also allows multiple stabilizer and rudder configurations to be tested on the

vehicle. The MAV is currently equipped with two downward mounted stabilizers. Separate magnetic actuators drive each rudder.

C. ONBOARD SYSTEMS

1. Drivetrain

A 7mm pager motor turns the flapping wing crank via a 26:1 reduction gear. The motor and gearbox are produced by Didel. The selected motor is highlighted in Table 5. Although rated for 1.20V, the motor is run between 5.0 and 7.4V. The crank and connecting rods were sized appropriately for this MAV to have the same proportions of its predecessors. The motor RPM, gear, and crank combination controls the flap frequency while the crank size and connecting rod length control the flap amplitude.

| Table 5. Didel Pager Motors | | | |
|-----------------------------|-------|-------|----------|
| Model | Rtd V | Rtd A | mass (g) |
| MNC-4S-10 | 1.20 | 0.120 | 0.46 |
| MNC-4S-24 | 3.00 | 0.125 | 0.46 |
| MNC-4-10 | 1.20 | 0.092 | 0.7 |
| MNC-4-40 | 3.00 | 0.075 | 0.7 |
| MNC-4L-10 | 1.20 | 0.120 | 0.7 |
| MNC-4L-40 | 2.40 | 0.060 | 0.7 |
| MNC-6S-10 | 1.20 | 0.120 | 1.3 |
| MNC-6S-30 | 2.40 | 0.080 | 1.3 |
| MNC-6-10 | 1.20 | 0.120 | 1.5 |
| MNC-6-3 | 0.80 | 0.267 | 1.5 |
| MNC-6L-10 | 1.20 | 0.120 | 1.5 |
| MNC-6-8 | 0.80 | 0.100 | 1.5 |
| MNC-6-85 | 0.80 | 0.094 | 1.5 |
| MNC-7-10 | 1.20 | 0.120 | 2.3 |

2. Battery

There are many potential battery choices from many companies. MAV electronics do not require a large discharge rate or power density. Energy density and the ability to be reused were determined to be the most important characteristics for the MAV energy source. For these reasons, rechargeable lithium polymer cells were selected. Kokam, E-Tec, Polycell, DWE, and ABF are some of the many LiPo battery suppliers. LiPo batteries are available with varying capacities (rated in mAh), max

currents (rated in A), and max discharge rates (C). For a given battery the maximum capacity is reduced with increasing discharge rate. At the time this report was published a final battery selection had not been made.

3. Servomechanisms

Conventional hobbyist radio-control servos are too large for the flapping wing MAV. The rudders are deflected using magnetic actuators. Magnetic actuators are sold as paired sets of coils and magnets from numerous vendors including Leichthy, Roomflight, Didel, EFlight Designs, BSD, and DWE. Actuators vary in weight from 0.11g to 2.3g and torque from 0.06 g-cm to 4.3 g-cm, although vendors will custom make actuators. Table 6 shows models that are readily available.

| Table 6. Actuators | | | | |
|--------------------|-------------|---------------|---------|--------|
| Brand | Model | Torque (g-cm) | Voltage | Wt (g) |
| Leichthy | Micro | 0.06 | 3.5 | 0.11 |
| Leichthy | Mini | 0.12 | 3.5 | 0.16 |
| Leichthy | Std | 0.22 | 3.5 | 0.25 |
| Didel | PicoBird | 0.38 | 3.5 | 0.33 |
| Leichthy | Std MX | 0.25 | 3.5 | 0.33 |
| RoomFlight | 4mm | 2.1 | 3 | 0.75 |
| Didel | NanoBird | 0.73 | 3.5 | 0.62 |
| Didel | MicroBird | 1.6 | 3.5 | 0.9 |
| EFlight Designs | Mini | 1.8 | 3.5 | 0.95 |
| BSD | Mini | 2 | 3.5 | 1 |
| RoomFlight | 3/8" | 2 | 3.5 | 1.3 |
| DWE | MA-50-t | 2 | 3.5 | 1 |
| Didel | MilliBird | 2.2 | 3.5 | 1.5 |
| EFlight Designs | Unliminator | 3.7 | 3.5 | 1.6 |
| EFlight Designs | Mega | 4.3 | 3.5 | 1.9 |
| BSD | Plug n Play | 4.3 | 3.5 | 2.3 |

4. Receiver

Four receivers are currently being tested on the NPS flapping wing MAV. The specifications of these four receivers are displayed in Table 7.

| Table 7. Receivers for Actuators | | | | | | | |
|----------------------------------|----------|----------------|------------|------|----------|-----------------|--------------|
| Manufacturer | Model | f (MHz) | Narrowband | Mode | Crystals | Complete Wt (g) | Bare Wt (g)* |
| Slowfly (DWE) | RFFS-100 | 35/72 | No | FM | GWS/UW1 | 2.1 | 1.7 |
| Micro Plane Solutions | MPS-CMB | 35/41/72 | Yes | FM | GWS/UW1 | 2.3 | 1.3 |
| JMP | JMP-RX | 35/36/40/41/72 | Yes | FM | GWS/UW1 | 2.8 | 1.9 |
| Pantraco | Micro9 | 868/900 | Yes | FM | N/A | 0.9 | 0.38 |

| Manufacturer | Model | Actuator Channels | Channel Expandability | Speed Controller (A) | Multicell (LiPo) Operation | Low-voltage Cutoff |
|-----------------------|----------|-------------------|-----------------------|----------------------|----------------------------|--------------------|
| Slowfly (DWE) | RFFS-100 | 2 | No | 1.0 | No | No |
| Micro Plane Solutions | MPS-CMB | 2 | +3 (0.1g) | 1.5 | 2-3 | Yes |
| JMP | JMP-RX | 2 | +1 (0.7g) | 1.5 | 2 (1.0g) | Yes |
| Pantraco | Micro9 | 2 | No | 2.0 | No | Yes |

The Slowfly receiver has a large bandwidth of 76kHz, compared to 10Khz of the other 72MHz receivers, making it more subject to interference. The MPS and JMP receivers can be upgraded to operate more actuators, or operate off of multiple LiPo cells. The high draw off the motor can drain all of the batteries stored energy. All receivers but the RFFS-100 cut power to the motor when the voltage supply is low. This feature is important in keeping the battery alive. Keeping the battery alive after it has discharged most of its capacity allows the pilot to maintain command of the control surfaces.

5. Payload

The payload carried onboard the MAV is a camera and video transmitter from MicroTek. The weights of the camera and transmitter stripped are 3.3 and 1.6g, respectively, and are shown in Figure 25 compared to a dime. The color camera captures 380 lines of resolution and has a 5V regulator built in. The transmitter which operates between 3.3-5V is matched for operating off of a single LiPo cell. A DIP switch allows the transmitter to be used on four different channels. Video is transmitted at 2.4GHz via an omni-directional antenna at 50mW.

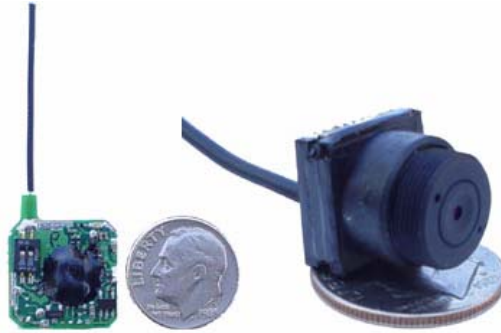


Figure 25. Video transmitter and camera
[www.microcameras.com]

V. FUTURE FOR MAVS

A. RESTRICTIONS

1. Communications

MAV communications pose several problems. Communication can be easily maintained through line-of sight; however, for ‘over-the-hill’ operation new methods must be developed. Another host UAV may be required to relay communications to the MAV. A larger airborne UAV or unmanned ground vehicle would be capable of relaying communication. Larger communication relay vehicles could stay within MAV LOS and carry stronger transmitters for increasing operational range. However, this requires a system of autonomously pointing the high gain antenna at the MAV. Larger UAVs are tracked using downlinked GPS telemetry. GPS receivers and antennas are currently too large and require too much power for MAVs. New lightweight methods of tracking MAVs or GPS receivers must be created.

Transmitter antennas also pose problems for MAVs. Small dimensional requirements limit antenna sizes, transmission frequencies, and range. Tightly packed electronic components are susceptible to electromagnetic interference and radio-frequency interference. The added weight of shielding components is also undesirable.

2. Current Off-The-Shelf Components and Sensors

For reduced costs, MAVs make use of current off-the-shelf (COTS) components. Using COTS equipment limits MAV design. MAV designers must select from a limited supply of motors, batteries, conventional radio-controlled hobbyist hardware, and cameras. Many of these components are not designed for high performance lightweight MAV operation. Also, current technology does not provide commercially available autopilot systems small enough to put on the smallest MAVs. Even though electric motors are made very small, the smallest electric motors have poor efficiencies.

MAVs although debatably stable in flight do not provide a stable platform for the camera. The lightweight vehicles are very susceptible to environmental disturbances. Small displacements caused by gusts or turbulence are very detrimental to video stability.

Gyro-stabilized systems offer a solution for larger vehicles but are too large for MAVs. Ideally, MAV ground stations will use software to stabilize the video.

Many ideologists see MAV sensors expanding beyond simple cameras. Sensors for detecting chemical and biological agents are very large. The smallest chemical sensors are around 5kg. Biological sensors are even larger. These types of sensors will require much more development before they will be of a weight suitable for MAV payloads [Ref.20]. An alternative concept would be to use the MAV as a remote Petri dish. The vehicle would be incapable of sampling and transmitting levels while in flight, however, upon return the MAV could be inspected for hazardous particles stuck to it. Experiments with simple sensors have been conducted to measure light waves outside of the visible spectrum. Such devices are probably too large for MAVs. Researchers are currently working with similar sensors that are much smaller but tuned for a specific frequency.

3. FAA Regulations

The FAA Unmanned Aerospace Vehicle Operations Working Group was created to investigate the need for FAA regulations specifically pertaining to the operation of UAVs. The FAA found that most UAV operations took part in special use airspace for DOD activities. The FAA recognized that technological advancements were cause for expanded commercial applications and civilian uses for UAVs. The FAA determined that not enough data was available to create extensive regulations for UAV flight. At this time, an advisory circular released in August of 1996 governs UAV restrictions. Currently, the FAA is allowing few UAVs to operate in the commercial sector by waiver only. Such waivers (FAA form 77111) are approved by the FAA on a case by case basis and most UAVs do not meet the criteria for the commercial application waivers. Civil operations of UAVs in the national airspace (NAS) must be conducted within the current air traffic control (ATC) system without interfering with manned flight. In addition to ATC clearance, out of line of sight UAVs must follow instrument flight rules (IFR) and must be equipped with a flight termination system (FTS) in the event of a catastrophic failure. NAS operation waivers require vehicle design criteria, maintenance, and pilot qualification. The FAA does not currently separate autonomous MAVs from larger UAVs. Autonomous MAV flight must also follow these regulations. The FAA is

expected to implement more UAV specific regulations as more data becomes available. MAV autopilot development will be significantly hindered if it continues to be constrained by the current regulations [Ref.21].

B. NOTABLE DEVELOPMENTAL PROGRAMS

1. Stanford Mesicopter Project

Researchers at Stanford are designing a multi rotating wing VTOL MAV. The researchers hope to create a flight control system that controls vertical and translational flight by manipulating multiple motors each driving a separate propeller. Stanford has successfully designed, fabricated, and tested the performance of 1.5cm rotors on a 3mm 325mg induction motor on external power. A four-rotor design has been manufactured and tested. The test platform successfully demonstrated a lift surplus. Stanford researchers believe that the surplus lift is enough to carry the batteries and control system. The control system is still under development. The weights of current off-the-shelf electronics are an order of magnitude too large for the Mesicopter. At its current scale, the Mesicopter demands custom fabricated avionics hardware and further development of MEMS technology [Ref.9].

2. SRI Mentor Project

Although SRI's SBIR funding was mainly for the EPAM development they conducted notable research and numerous tests on flapping wing dynamics. The Mentor platform is comprised of four wings in a clap-fling-clap configuration and a tail section. The Mentor performed hovering flight without a test-stand. Four independently actuated control fins are located below the vehicles center of gravity. Ideally, the control fins are used to control the Mentor in hovering and transitional flight. SRI reports that the 3-axis gyro and PID control system kept the vehicle very stable in altitude. Translational flights were not attempted. Battery powered flights never exceeded 20 seconds. Although the NiCad batteries selected had enough stored energy for 90 seconds of flight they were not capable of continuously discharging power at the rate necessary to maintain hovering flight for more than 20 seconds. The Mentor program shows the potential of flapping wings for powering hovering MAVs [Ref.22].

3. Micro-Sized Jet Engines

In 2000 DERA claimed to have successfully produced and demonstrated a micro scale jet engine called “Microjet”. The tiny powerplant was designed to be used for MAVs. The engine is 13mm long, 5mm in diameter, weighs less than 2g, and runs off of hydrogen peroxide. DERA claimed to have used the engine as a pure jet and as a higher efficiency ducted fan unit. A thrust of 0.063N gives the engine a 75:1 thrust to weight ratio. DERA claims endurance up to an hour on its test stand; however no literature is available showing any further demonstrations or use of this engine on a MAV since the report was published in July of 2000 [Ref.23].

Many programs are still in the works to shrink down jet or gas turbine engines to be used for MAV propulsion. DERA has already produced their “Microjet” and MIT is currently developing their MEM compressor, turbine, and combustion chamber for a MAV microturbine propulsion system. The goal is a high-revving gas-turbine paired with an electric generator with a combined weight of less than a gram that together will be smaller than a shirt button. Similar to ICE, fuels must pass through microscopic ports. These ports plug easily by debris in the fuel, severely hampering the reliability of the engine. Whereas DERA has claimed to run theirs on a test stand, each component of MIT’s invention is still under development.

C. FEASIBILITY FOR THE MISSIONIZATION OF MAVS

Although both the MicroSTAR and Black Widow flew, DARPA’s MAV effort officially ended in 2000. Many companies such as MLB and Lockheed abandoned their projects. Although the concept was shown to be possible, many program managers have suggested that a useful UAV at a size that small was unrealistic in the near future with current technology.

In 2002, DARPA started the organic air vehicle (OAV) program. Numerous companies such as Allied Aerospace and Honeywell worked with the US Army to develop unmanned ducted fan helicopters. Funding of OAV-2 in 2004 shows DARPA’s attention being on larger vehicles [Ref.24].

Although government funding of MAV projects has been reduced, they still have significant potential to become missionized platforms. Current off-the-shelf technology and manufacturing processes are still advancing. In the long run, components will be small and cheap enough to mass produce swarms of MAVs with multiple sensors. Researchers have only begun to probe the aerodynamics of MAV flight. Although expensive, various experimental techniques and computer codes are already available for analyzing the low Reynolds number flow over MAV wings. With a greater understanding of phenomenon that occur over small MAV and flapping wings, more efficient designs can be made to take advantage of these effects.

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VI. RECOMMENDATIONS FOR FURTHER WORK

A. MAV HARDWARE TESTING AND OPTIMIZATION

More testing is required to assess which of the four receivers is best suited for the MAV. Experiments should be conducted using each receiver to determine maximum range, resistance to interference and dropout, and power draw. Tests with different battery packs should be conducted to determine thrust and endurance ratings for the current flapping wing configuration. Such testing will be important in the future design alterations to the MAV. The MAV was constructed so that many physical parameters could be easily adjusted for tuning the MAV. Experiments should be conducted with different lifting wing twist, camber, dihedral; flapping wing size, flap amplitude, and hinge elasticity; and rudder configurations.

B. WIND TUNNEL TESTING AND FLOW VISUALIZATION

Additional wind tunnel testing of the NPS flapping MAV is necessary to understand the low Reynolds number flow dynamics over the MAVs lifting and flapping wings. Wind tunnel testing to determine lift and thrust forces of the MAV is necessary to correlate the MAVs power output and planform size to maximum thrust and maximum weight. CFD work using Navier-Stokes equation based codes should also be pursued to investigate the highly viscous flow over MAV airframes.

C. EXTENDING COMMUNICATION RANGE

A separate study should be performed to evaluate potential methods to maintain communications with the MAV. When the MAV is out of line of sight, current line of sight communications cannot be utilized. If a second unmanned vehicle is used to relay the MAVs communications, a method to track the MAV must be developed and tested.

D. VISION BASED GUIDANCE

A vision based guidance system would be very useful for indoor reconnaissance or contact tracking missions. Currently, rudimentary experiments with vision guidance have been mostly unsuccessful. University of Florida and Georgia Tech engineers experimented with numerous passive systems for extracting and tracking feature points. Further developments included image registration, object detection, and object identification. Carnegie Mellon combined video feed with range estimations from laser scanning on a small radio-controlled helicopter for 3D terrain mapping. Although Carnegie Mellon researchers were able to determine the vehicle states with offline computer applications, they found that in-flight determination of the vehicles position and orientation had many additional difficulties. More work with the Kalman filtering methods used by these researchers should be continued because it has the potential for use in vision guidance for small and micro air vehicles [Ref.25].

E. GROUND LOCOMOTION

Many engineers have attempted to develop a MAV that is capable of take-off under its own power. The ability for a MAV to fly close to a target of interest, land, crawl into a position, collect intelligence, and then take-off under its own power is very desirable. Because of its low weight and take-off velocity, the NPS flapping wing MAV has the potential to take off under its own power. Multiple designs for ground locomotion should be experimentally fitted on the MAV in an attempt to achieve self-powered launch.

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